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Solutions to sustainability in construction: some examples

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Abstract

Many innovative solutions to sustainability have been developed or adopted in the past in various sectors of construction. Some of those related to geotechnical engineering are presented in this paper. These include the use of biocement as an alternative to Portland cement for soil improvement, the use of bio-desaturation as a method for mitigation of liquefaction hazard, the use of plastic waste to make construction products, and the use of the NEUSpace method for land reclamation in deep water to reduce the usage of fill materials.

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Keywords: Construction; geotechnical engineering; liquefaction; sustainability; waste.

1. Introduction

Construction is a sector that consumes a huge amount of construction materials that have to be made through the use of a large amount of natural resources and energy. One typical example is Portland cement. When we have to construct a building or bridge over soft ground, the soft soil needs to be treated. There are a number of ways to strengthen soft or weak soil. One of the common approaches is to use cement or chemicals to treat the soft soil in order to increase the load bearing capacity or the so-called shear strength of soil. The same process can be used to reduce the water conductivity of soil or the rate of water flow in soil. This is necessary when there is a need to prevent water from flowing in the ground, for example, for cutting off contaminated groundwater flow. In the above

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cases, cement or chemicals are used as a binder to mix with soil to either increase the shear strength or reduce the water conductivity of soil. However, the use of cement or chemicals for construction or soil improvement is not sustainable in the long run as cement or chemicals require a considerable amount of natural resource (for example limestone) and energy to produce. The production process also generates carbon dioxide, dust and possibly other toxic substances and thus is not environmentally friendly. The use of cement or chemicals for soil improvement is also expensive and time consuming. Therefore, any solutions that can reduce the usage of cement in construction will contribute directly or indirectly to sustainability in construction. The first way to reduce the use of cement is to develop new and sustainable construction materials that can reduce the use of cement or chemicals for geotechnical applications. Biocement is one of such materials that can be used to replace cement for soil improvement. The second approach is to use methods that do not require the use of cement or that can minimize the use of cement. The third is to use other waste materials such as fly ash to replace cement partially for soil improvement.

Another area that can be improved to promote sustainability in construction is to reduce earth cutting or marine dredging as a way to supply fill materials. The use of a large amount of fill materials for construction such as land reclamation means more earth cutting or marine dredging which can deprive natural resource and generate negative impacts on environment. The transport of a large amount of earth also affects the environment by generating pollution and causing social concerns such as traffic congestion. There are a number of ways to reduce the use of a large amount of fill materials. One of them is to adopt the so-called NEUSpace method proposed by Chu et al. (2015).

The methods mentioned above are described in the following.

2. Use of biocement as an alternative to Portland cement

Using the latest microbial biotechnology, a new type of construction material, biocement, has been developed as an alternative to Portland cement or chemicals [1], [2]. Biocement is made of naturally occurring microorganisms at ambient temperature and thus requires much less energy to produce. It is sustainable as microorganisms are abundant in nature and can be reproduced easily at low cost. The microorganisms that are suitable for making biocement are non-pathogenic and environmentally friendly. Furthermore, unlike the use of cement, soils can even be treated or improved without disturbing the ground or environment as microorganisms can penetrate and reproduce themselves in soil. Harnessing this natural, unexhausted resource may result in an entirely new approach to geotechnical or environmental engineering problems and bring in enormous economic benefit to construction industries. The application of microbial biotechnology to construction will also simplify some of the existing construction processes. For example, the biocement can be in either solid or liquid form. In liquid form, the biogrout has much lower viscosity and can flow like water. Thus, the delivery of biocement into soil is much easier compared with that of cement or chemicals. Furthermore, when cement is used, one has to wait for 28 days for the full strength to be developed, whereas when biocement is used, the reaction time can be much reduced if required.

The principles of microbial treatment are to use the microbially-induced calcium carbonate precipitation or other approaches to produce bonding and cementation in soil so as to increase the strength and reduce the water conductivity of soil. A number of studies have been carried out in recent years [1]-[5]. Much of the work still stays at the experimental stage. However, the scale of treatment has increased rapidly with time and has reached 100 m^3 in the recent years [4].

The microbiological processes induce calcium carbonate crystals, other minerals or slimes as illustrated by examples shown by Van der Ruyt and van der Zon (2009) [4], Van Paassen et al. (2010) [5] and Chu et al. (2012) [6]. Those minerals or slimes act as cementing agencies between sand grains to increase the shear strength of soil and/or to fill in the pores in soil to reduce the water conductivity as illustrated schematically in Fig. 1. The two processes to increase strength and reduce conductivity have been called biocementation and bioclogging respectively [2]. The process to deliver the biocement in-situ to achieve biocementation or bioclogging is called biogrouting. As the viscosity of biogrout is low, it is possible to pump in the biogrout into the ground without mixing for sandy soil. This will enable the construction process to be simplified. The existing study so far shows that the biocement method is effective in both increasing the shear strength and reducing the water conductivity of soil.

By using the microbially-induced calcium carbonate precipitation method, the shear strength of soil can be increased. When cement or chemicals are used to treat soil, the amount of improvement in the shear strength of soil is dependent on the amount of cement or chemical used. Similarly, when biocement is used, the shear strength of soil is affected by the amount of metal precipitation. One way to measure the shear strength of soil is by simply compressing a soil column in between of two rigid plates, the so-called uniaxial compression test. The shear strength measured by this method is called the uniaxial compressive strength (UCS). In one study by Van der Ruyt and van der Zon (2009) [3], the UCS of biocement treated sand was measured for specimens having different calcium carbonate contents. The results are shown in Fig. 2. It can be seen that the UCS strength increases with increasing calcium carbonate content. The highest UCS obtained is 27 MPa. For normal applications, the UCS strength required is less than 3 MPa. This will only require a calcium content of 100 to 200 kg/m^3. To achieve the same UCS strength for sand using cement grounting, the amount of cement used would be between 250 to 300 kg/m^3. As the production of biocement can be cheaper as discussed by Ivanov and Chu (2008) [2], the overall cost for biogrouting can be potentially lower. Another advantage is that when cement grouting, it takes 28 days for the UCS to reach the targeted value. However, when biocement is used, full strength can be gained in a much shorter time if required.

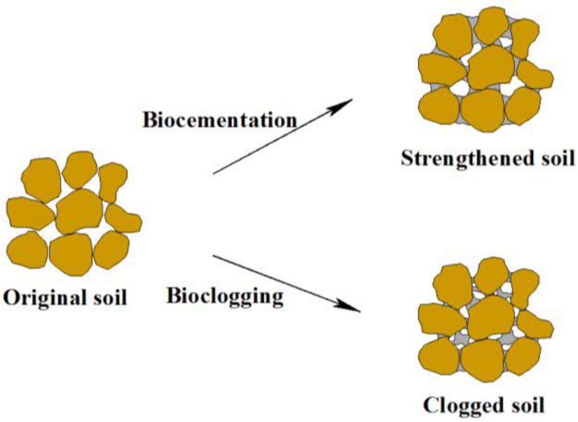

Fig. 1. Schematic Illustration of biocementation and bioclooging process

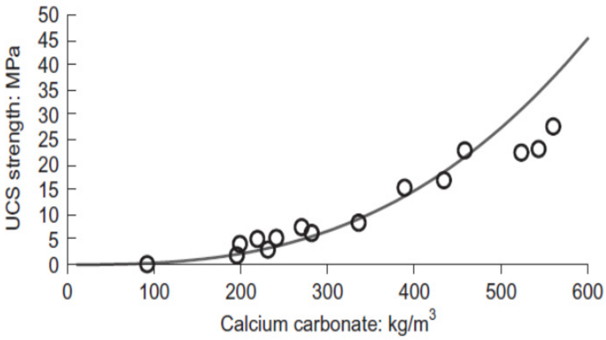

Fig. 2. The unconfined compression strength (UCS) versus calcium carbonate content relationship for biocement treated sand (after Van der Ruyt and van der Zon, 2009)

3. Bio-desaturation for mitigation of liquefaction hazard – a method to reduce the use of cement

One example to illustrate the methods to avoid or reduce the use of cement is to use biogas to mitigate the damage of liquefaction caused by earthquake [8]. Sol liquefaction refers to a phenomenon in which a soil is transformed into a substance that acts like a liquid in response to an external action such as earthquake. When liquefaction occurs, the ground losses completely it's bearing capacity and undergoes large deformation. Soil liquefaction normally occurs in saturated sand deposits during earthquake. The ground shaking will cause the water pressure in soil or the so-called pore water pressure to build up. When the pore water pressure has increased to a certain point, soil liquefaction will occur. Soil liquefaction has been one of the major causes for serious damages and earthquake related disasters. More recently liquefaction was largely responsible for extensive damage to residential properties in the eastern suburbs and satellite townships of Christchurch, New Zealand during the 2010 Canterbury earthquake and more extensively again following the Christchurch earthquakes that followed in early and middle 2011.

Common methods that can be adopted for mitigation of soil liquefaction include densification and ground modification using cement or chemicals. As the extent of soil to be treated for mitigation of liquefaction hazard is usually very large, the amount of cement or chemicals used can be very substantial.

A new liquefaction mitigation method that can avoid the use of cement is the so-called biogas method [8]. In this approach, tinny gas bubbles are generated in-situ in saturated sand at where liquefaction may occur. When saturated sand is made slightly unsaturated by the inclusion of gas bubbles, the amount of reduction in the pore water pressure generated in sand under a dynamic load will be greatly reduced. Based on our research, if we replace only about 5% of water by gas by volume, we will be able to increase the liquefaction resistance of loose sand by more than 2 times.

It is not easy to introduce gas into ground. Pumping can be used. Fig. 3 shows a schematic illustration of how to carry out air pumping for liquefaction mitigation. However, the distribution of gas bubbles introduced by pumping will not be even. Furthermore, the gas pumped into ground tends to present in the form aggregated gas pockets rather than individual bubbles. As a result, the gas tends to escape from the ground. One of the most effective ways to introduce tinny gas bubbles in-situ is to use microorganisms. This method has the following three advantages over the existing methods: (1) Biocement is like water in the liquid form and flow easily in sand. Gases can be generated easily by bacteria anywhere underground by consuming only a small amount of energy. Thus the biogas method will be much more cost-effective than any other methods. As the scale of treatment for liquefaction is normally very large, the potential economic benefit is significant; (2) The gas bubbles generated by bacteria can be distributed more evenly than other means. This is because biocement can be delivered by water flow in sand and the gas bubbles are generated in-situ rather than pumped; (3) The gas bubbles generated by bacteria can be much smaller. It is necessary for the gas bubbles to be tinnier so the gas bubbles are less prone to escaping from the ground.

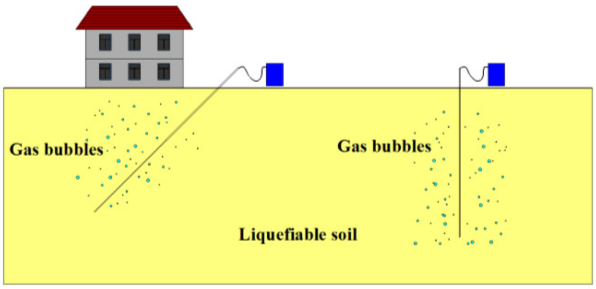

Fig. 3. Mitigation of soil liquefaction by air injection

Some model tests using a laminate box and a shake table to generate ground motion were carried out [7]. A comparison of ground settlement for a fully saturated sand layer and a sand layer treated with biogas is made in Fig.

4. The settlement is expressed as a settlement ratio with the settlement for fully saturated sand as 100%. It can be seen from Fig. 4 that with only 5% of gas replacement, the ground settlement generated under ground shaking with an acceleration of 1.5 m/s^2 can be reduced by more than 90%. Thus, the biogas method is effective in preventing the occurrence of soil liquefaction or reducing the damage caused by liquefaction.

Compared with conventional soil liquefaction mitigation methods, the biogas method has some significant advantages. Conventional methods, such as compaction, cementation, lowering ground water table, and pore pressure relief using vertical drains, etc., are usually expensive when applied to large areas, or need high maintenance. However, the biogas method is rather cost effective. One reason is that density of gas is very small, about three orders of magnitude smaller than solid and liquid, so relatively small amount of solid or liquid substrates can produce relatively large volume of gas. The other reason is that the operation is easy, because the liquid phase substrates can easily spread throughout the sand layer, thus the construction fee can be largely reduced. Other advantages of the biogas method include environmentally friendly, energy saving, and time saving. These advantages make the biogas method a very promising way to solve liquefaction-related problems in large areas, such as lateral spreading.

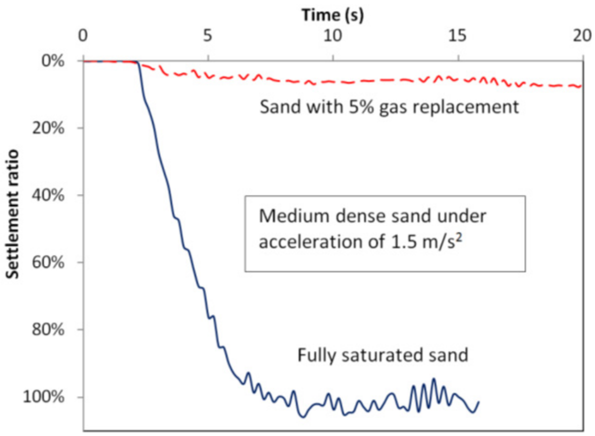

Fig. 4. Comparison of ground settlement induced by ground shaking under an acceleration of 1.5 m/s^2 for a saturated sand layer and a sand layer with 5% gas replacement.

4. Use of plastic waste to make construction products

Plastic waste has become a visible and significant component in municipal solid waste and continues to increase due to an increasing use in plastic. According to the National Environmental Agency of Singapore, 869,000 tons of plastic waste was produced in Singapore in 2014 and only 9% of which was recycled. As most of the plastic is not biodegradable, plastic waste disposal has raised many concerns on environmental and social issues. One way to solve this problem is to convert plastic waste into value-added lightweight construction products.

Plastic water bottles or cups are normally made of Polypropylene (PP) which has a melting point of 160 ^{0}C. Plastic after melting can be used as a bender to bind clay or sand by mixing the melted plastic with clay or sand at a PP to soil ratio of 10 to 20% by weight. This method can be used to make construction materials such as those shown in Figs. 5 and 6. The cylinders or bricks made in such a way have a compressive strength as high as 10 MPa as shown in Fig. 7 [6]. The use of plastic will also result in a product with low unit weight. Light-weight is an important property that is desired as a construction material. So the products made of plastic will be value added and more useful than other conventional construction products.

Figure 5. Marine clay-Polypropylene (PP) specimens with PP/Soil ratio of 10%

Figure 6. Bricks made of (a) marine clay-Polypropylene and (b) sand-Polypropylene with PP/marine clay or PP/sand ratio of 20%

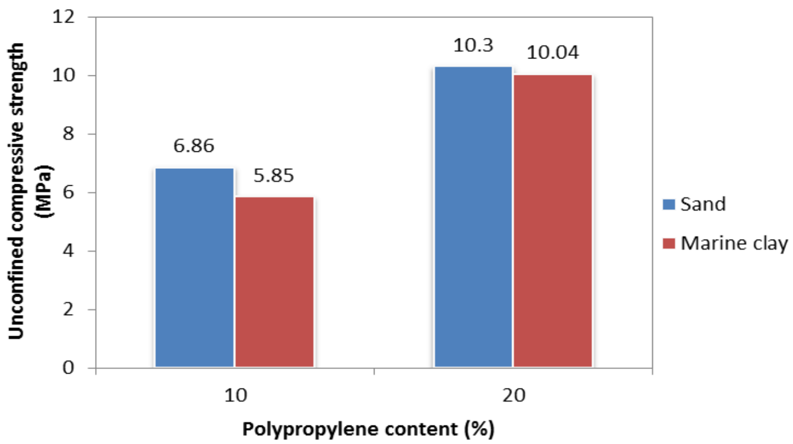

Figure 7. Unconfined compressive strength vs Polypropylene content

5. NEUSpace method for land reclamation in deep water

When land reclamation has to be carried out in a water depth more than 15 m, it may not be economical or sustainable to use earth fill. One method is to use large-sized cylindrical structures for land reclamation and creating space underwater at the same time as illustrated in Fig. 8. This so-called NEUSpace method is currently being studied [7]. NEUSpace stands for NEw Underwater Space. The method is to make use of the sea space to construct underwater infrastructure and at the same time use the top-side of the infrastructures as reclaimed land. Using this method, the amount of fill materials required can be greatly reduced and more space can be created.

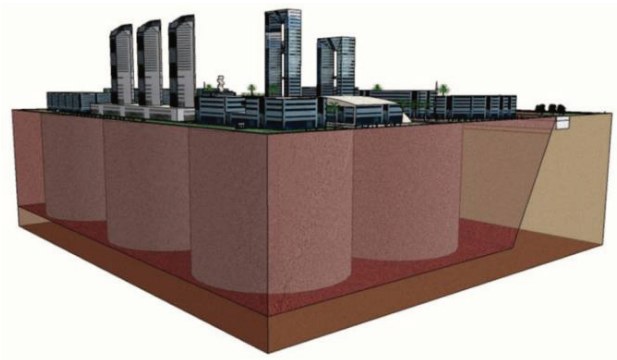

Figure 8. New method for land reclamation and underwater space creation

The large-scale concrete cylindrical structures can be installed using a method similar to the installation of seawalls or suction anchors for offshore oil platforms. One example of using this method for the construction of a seaport is shown in Fig. 9.

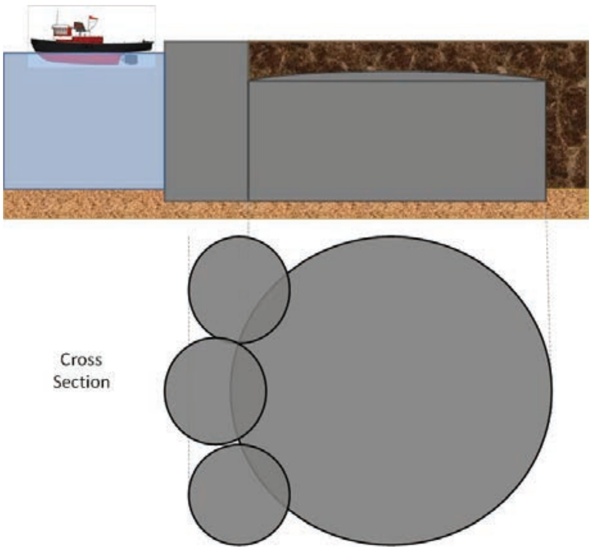

Figure 9. One method for the construction of a sea port using the NEUSpace method

6. Concluding remarks

Several methods that could improve the sustainability in construction related to geotechnical applications have been presented. It can be seen that we can reduce the usage of cement by using biocement as a substitute, using different construction methods that require less use of cement, and using waste such as plastic to make construction products. To carry out land reclamation in deep water, a more sustainable method is to the NEUSpace approach to cut down the usage of a substantial amount of fill materials.

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